UNC-AM-13-006

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Facilitating Decision Choices With Cascading Consequences in Interdependent Program Networks

7 January 2013

by

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and

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Software and Information Systems

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Prepared for: Naval Postgraduate School, Monterey, California 93943

ACQUISITION RESEARCH PROGRAM
GRADUATE SCHOOL OF BUSINESS & PUBLIC POLICY
NAVAL POSTGRADUATE SCHOOL

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **07 JAN 2013**	2. REPORT TYPE	3. DATES COVERED **00-00-2013 to 00-00-2013**

4. TITLE AND SUBTITLE
Facilitating Decision Choices With Cascading Consequences in Interdependent Program Networks

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of North Carolina at Charlotte,9201 University City Blvd,Charlotte,NC,28223

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**77**	

The research presented in this report was supported by the Acquisition Research Program of the Graduate School of Business & Public Policy at the Naval Postgraduate School.

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Abstract

Acquisition research has recently laid emphasis on the study of the cascading effects of interdependencies in the joint space of Major Defense Acquisition Programs (MDAPs). We are interested in proactively modeling the non-linear cascading effects of interdependencies in highly dependent networks. Specifically, in this report we examine DoD acquisition in the context of when MDAPs exchange and share resources for the purpose of establishing joint capabilities. Our hypothesis is that examining the interdependent regions among MDAPs from multiple perspectives using non-linear methods will allow for “what-if” analyses and will help decision-makers gain insight on the cascading effects of perturbations and take appropriate measures to handle them. Additionally, we also ascertain whether a popular decision-theoretic model for decision-making and planning for cascading effects in the face of uncertainty is appropriate to study the cascading effects among MDAPs. Our approach is to use a case study to determine whether the data required to build an effective decision-theoretic model is available. We also capture the data investigation process and identify the challenges that were encountered. Our results show that it is possible to recast the study of cascading effects in MDAPs as a sequential decision problem. We describe the informational value in the existing data and challenges inherent in the data collection process.

Keywords: Major Defense Acquisition Programs (MDAPs), non-linear cascading effects, dependent networks

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Acknowledgements

We are grateful to Dr. Maureen Brown for providing us access to MDAP data and her guidance as we learned to navigate the world of MDAPs, and Graham Owen for assisting us in the data-gathering process. We also thank Mr. Robert Flowe for his insightful comments on drafts of this document.

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About the Authors

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I. The Joint Space of Major Defense Acquisition Programs Networks

It has been shown that data are the foundation for decision-making in the acquisition environment. The DoD has spent a significant amount of effort working across the organization to identify useful sources of data and to conduct analyses. The importance to acquisition research of studying Major Defense Acquisition Programs' (MDAPs) interdependencies was emphasized during the 2012 Annual Acquisition Research Symposium by the introduction of a new panel titled Predicting Performance and Interdependencies in Complex Systems Development. Prior research has established that MDAPs are demonstrably interdependent and that they can be thought of as networks of interdependent programs (Lewin, 1999; Flowe, Brown, & Hardin, 2009). Also, the acquisition paradigm established in statute (10 U.S.C. 2434; Defense Acquisition Workforce Act, 1990), in policy (DoD 5000.02; Under Secretary of Defense for Acquisition, Technology, and Logistics [USD(AT&L)], 2008), and in regulation tends to favor the notion of MDAPs as being independent, which would cause exogenous factors caused by interdependence to be overlooked or misinterpreted.

Although it is critically important to understand the program interfaces and interdependencies, there are few tested and proven tools for program managers and acquisition executives to probe the joint space or to track the cascading effects that the joint space might trigger. There is reason to believe that the exogenous issues generated from the shared domains remain unnoticed to the extent of causing the program to potentially experience severe performance degradation (Brown, 2011). The complexity of the joint environment is likely to have a direct bearing on acquisition activities. The precise effect on acquisition, and its resulting managerial implications, are, as of yet, unknown. We believe that given the frequency with which government agencies are moving toward joint initiatives, the findings of this research project based on DoD programs may prove instrumental to a wide-ranging audience.

Furthermore, at the 2012 Acquisition Symposium, Dr. Frank Kendall III, the Under Secretary of Defense for Acquisition, Technology, and Logistics (USD[AT&L]), discussed the DoD's strategic priorities, especially around acquisition. These priorities included achieving affordable programs that execute well and improving efficiency (via Better Buying Power and other initiatives).

Along with other researchers (Brown & Owen, 2012), we have begun to harness a network-centric approach to study DoD acquisition and focus on an MDAP network of interrelated programs that exchange and share resources for the purpose of establishing joint capabilities. Some work (Zhao, Gallup, & MacKinnon, 2012) has been done to analyze the unstructured and unformatted acquisition program data using a data-driven automation system called Lexical Link Analysis (LLA). LLA is used to determine the correlation between system interdependency and development costs in an effort to enable acquisition researchers and decision-makers to recognize important connections that form patterns derived from dynamic data collection. In other work (Han, Fang, & DeLaurentis, 2012), a Bayesian Network (BN) method is used to assess the cascading effects of requirement and systems interdependencies on risk in an effort to effectively analyze alternatives in a capability-based acquisition strategy. The technique is evaluated within a synthetic network and identifies critical systems and requirements.

This research seeks to understand and model the behavior of non-linear cascading effects in the joint space of MDAPs, where their transactions form interdependencies. The transactional flows in and out of MDAPs collectively form networks of interdependent programs that can be examined to conduct scenario planning or "what-if" analyses. These what-if analyses will help decision-makers gain insight on the cascading effects of perturbations and take appropriate measures to handle them. We develop models that can address what-if scenarios such as the following: What if my partner reneges on a funding obligation? What if Congress alters my funding? How will the perturbation affect my partners? The research also identifies and enumerates the characteristics in the existing MDAP data that are

critical to building a complete model of MDAP behavior and discusses the challenges in acquiring some of these data so that appropriate governance mechanisms can then be isolated. This data acquisition process is emphasized as much as the behavioral findings, with the hope that the lessons learned from the process will allow for more accurate and complete data gathering and modeling in future iterations of this work.

The MDAP data that we analyze include Selected Acquisition Reports (SAR), Defense Acquisition Executive Summaries (DAES), and Program Element (PE) documents over multiple years. Although our aim is to work on the entire collection of MDAPs, we observe that this eclectic conglomeration of information is highly unstructured, significantly inordinate, and unmanageably colossal for manual analyses. Hence we focus on a case study that contains a small set of existing MDAPs. We use fictitious names (e.g., MDAP_A, MDAP_B, etc.) to retain confidentiality of individual program information. In this case study, we do an in-depth analysis of the data and study their complex interrelationships from multiple perspectives with the hope that some of our observations and lessons learned about MDAPs and the analysis process can then be scaled to the entire network.

We study whether performance breaches correlate with interdependency characteristics in the context of a small MDAP network. As a consequence of this work, in future studies we can model the effects of acquisition decisions or program outcomes, such as a breach at a node or resource cutoff in some in-flow, and predict their likely effects. We can extend that to conjunctures of breaches or breaks in the flows. Similarly, we can determine the most robust and weakest programs in the system (i.e., those most and least likely to have breaches or fail). We also can use the model to examine the changes to the system that might increase its robustness.

The significance of the research is three-fold:

- It aims to forge new ground in identifying the effects of interdependency on acquisition and, if needed, uncovering early

indicators of interdependency risk so that appropriate governance oversight methods can then be isolated.

- It provides insight into the nature of the available data and whether they can support the use of non-linear methods to detect and prevent cascading consequences.
- It verifies using a small use-case the viability of a decision-theoretic model to describe the sequential decision-making process inherent to MDAPs. This model, which will be implemented in future work, will capture uncertainty in action outcomes and information about neighboring nodes.

A. Research Methodology

To perform this study, we designed a methodology with four goals. We first selected a small subset of inter-related MDAPs based on a set of criteria to form our case study. We defined Goals 1 and 2 to determine whether the MDAP data in the form of the SARs, DAES, and PEs is sufficient to identify the effects of interdependency on acquisition and uncover any early indicators of interdependency risk. These goals also determined whether a decision-theoretic model in Goal 3 is a feasible next step. Having verified that this is the case, we then formulated a decision-theoretic model. Finally, we captured the essence of the data acquisition process for our study and the lessons learned.

Goal 1: Identify highly dependent parts of the MDAP network:

- What are the essential features of the network that reveal the joint space dynamics?
- What are the relative priorities associated with these features and how do they affect the network relationship?

Goal 2: Analyze and understand the data available from MDAP performance reports to extract features of network dynamics:

- What are the local issues that lead toward breach or near-breach situations?

- How often and why do the local mitigation efforts fail to improve performance?
- How do we identify the non-local issues that result from the interdependencies?
- Can we determine the cascading effect through the network?

Recognizing that most acquisition decisions are framed by the assumption of programmatic independence, exogenous effects are not well represented in acquisition policy or practice. Therefore, we approached Goal 2 from two perspectives: a *local perspective* in which the analyses are based solely on the individual program's own data, and a *non-local perspective* in which the analyses are based on the data of MDAPs existing in the joint space of the individual program. We believe lessons learned from these analyses should enable the stakeholders to take appropriate measures to improve the performance of the programs.

Goal 3: Identify the building blocks necessary for a decision-theoretic model that harnesses the Decentralized-Markov Decision Process (DEC-MDP) formalism (this model will be implemented in future work):

- What are the essential characteristics of the MDAP network that justify a DEC-MDP model?
- How can the MDAP network be modeled as a decentralized system?
- What are the key challenges in the design of the DEC-MDP?
- What essential features should the DEC-MDP model incorporate for better predictability?

The DEC-MDP is a sub-class of decentralized, partially observable MDP (DEC-POMDP; Bernstein, Givan, Immerman, & Zilberstein, 2002) that we propose to use to model the behavior of the MDAP network. A state is a snapshot in time of the MDAP's status that consists of crucial local and non-local information. A policy is a mapping from a state to an action. This formalism would allow the MDAP to execute the appropriate local policy to achieve higher performance. Our aim is to define a computationally tractable model.

Goal 4: Understand the characteristics of the existing data resources:

- What are the challenges to pre-process the existing data?
- What key information do we gain from the existing data?
- What are the key limitations in the existing data?
- What are the most relevant authoritative data sources?
- What subset of this data is analytically useful?
- What are the data requirements to design a complete DEC-MDP model?
- How can the various program-related documents be integrated in a coherent and meaningful fashion to aid decision-makers as well as researchers to build complete models?

Goal 4 recommends what should be done to capture information so that the decision-making process becomes efficient and complete. It also opens the discussion to alternative sources of data and the notion that the DoD collects data that could be improved for analytic purposes.

B. Summary of Findings

Our findings indicate that MDAP-related data characteristics support the multiple-perspective study of perturbations, and it should be possible to recast the study of cascading effects as a sequential decision problem. We also note that when using manual analysis it is crucial to consider the uncertainty in action outcomes in the decision-making process and that a non-local perspective may help explain a performance breach in situations where a solely local perspective does not. We observe that the conditions that apply to the acquisition oversight and management context are particularly well suited to future analysis using decision theory, specifically sequential decision-making based on incomplete information, the need to support various possible outcomes over time to support effective decision-making, the availability of time-series data to help build the MDP model, etc. This verifies our conjecture that decision theory is a good avenue to study interdependencies in the

MDAP network and to capture early indicators of interdependency risk. This work also identifies the need to have access to large-scale data (of many MDAPs over several years) to build an accurate full-scale decision-theoretic model. This is the basis for our proposed research for the next phase of this project where we plan to design tools for large-scale automated batch processing of MDAP data using text and image analysis. Finally, we have captured the informational value in the existing data and challenges inherent in the data collection process with respect to their role in isolating risks and initiating appropriate government oversight methods.

The rest of the paper is structured as follows: We first identify the network dependencies among the MDAPs and define a sample network for analyses (Goal 1); we then investigate the local and non-local causes for degradation in performance of the nodes in the sample network (Goal 2); then we present the DEC-MDP model formulation (Goal 3) followed by observations made about the characteristics of the available data (Goal 4); and, finally, we conclude with the lessons that we learned through this process.

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II. Network Model

In this section, we first describe various MDAP performance reports and discuss their significance in the light of networking dependencies among the MDAPs. We also define a sample funding network from our chosen MDAPs in an effort to investigate its performance. Specifically, we define a process to choose an MDAP program to be the focus of our investigation and identify its immediate network based on the interrelationships it maintains with neighboring MDAPs. We will use the lessons learned from the analyses of this sample network to build an accurate decision-theoretic model.

A. Available Data Resources on MDAP Performance

The information pertaining to acquisition research is overwhelming and multifarious. It appears to be a daunting task for acquisition researchers, let alone program managers, to integrate and understand the vast and dynamic data in a coherent way. We use the following set of data sources to define the interrelationships and dependencies among the MDAPs from a network-centric viewpoint:

- Monthly DAES reports that provide an early-warning report on the status of some program features such as cost, schedule, performance, funding, and so forth;
- SARs that summarize the latest estimates of cost, schedule, and technical status to be reported annually in conjunction with the president's budget; and
- R-docs used to justify the congressional budgeting process.

B. Types of Interdependent Networks Within the MDAP Domain

In addition to the above data sources, program managers also report on four external interdependencies: (1) data interdependencies with other DoD programs, (2) funding received from other DoD programs, (3) contractor interdependencies,

and (4) budgeting/spending authority interdependencies. This information is useful in identifying four types of interdependency networks among the MDAPs. As an example, Figure 1 depicts 989 interdependencies of various types (resource, material, authority, etc.) that were extracted from a DAES report describing the 78 MDAPs in 2010. We claim that the existence of a link between one program and another provides a fairly robust basis for asserting there’s some sort of interdependence, and for building a hypothetical program network for the purposes of the analysis. We also note that MDAP programs will have interdependencies with non-MDAP programs. For example, the Joint Strike Fighter program identifies data and funding interdependencies with the Italian, German, and French defense departments. In the current dataset, 17% of the interdependencies are outbound, 37% are inbound, and 45% are bidirectional. As such, the flows in and out of a node can be examined to conduct scenario planning or what-if analyses.

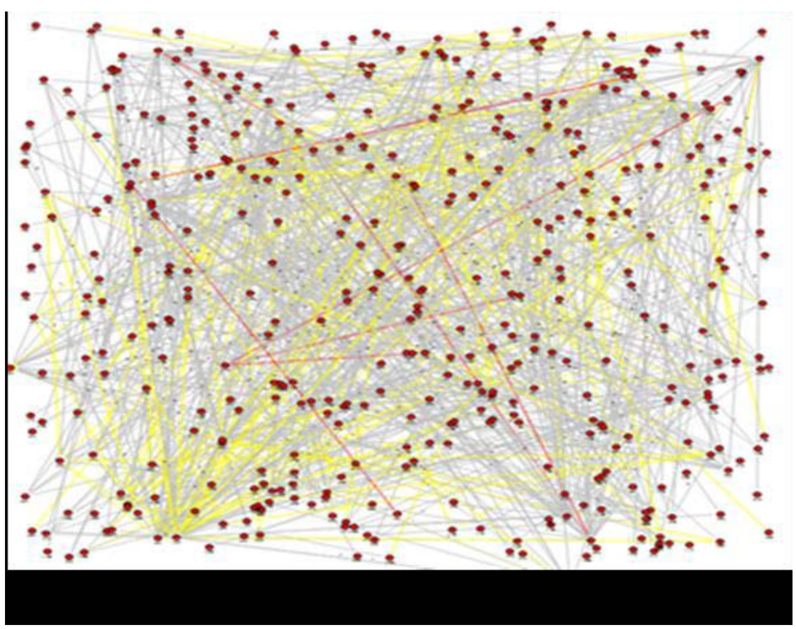

Figure 1. MDAP Interdependencies in 2010

C. Case Study of MDAP_A Funding Network

We choose to do a case study because of the characteristics of the data. MDAP_A, a communications program initiated in 2004 whose program name has

been scrubbed for confidentiality purposes, is the central MDAP for our study. This program is our focus because (a) the data available about this program are significant, and (b) between the years 2006 to 2010, it experienced multiple Acquisition Program Baseline (APB) breaches and percentage increases in Program Acquisition Unit Cost (PAUC), making it a critical node for reference. PAUC is defined as the ratio of the current Program Acquisition Cost to the Program Acquisition Quantity. PAUC combines both the research, development, test & evaluation (RDT&E) appropriation (for the engineering development of the program) as well as the Procurement appropriation (for the production of the system), and is sensitive to both changes in development and production funding as well as changes in the number of units procured. This makes it a particularly worthwhile metric of overall program performance.

Using information about the funding partners of MDAP_A, we define a logical funding network shown in Figure 2.The other nodes in the graph are neighbor programs of MDAP_A that share common funding agencies. The funding network is defined based on the number of PEs that funded the MDAP RDT&E efforts. PE is the code number assigned by the comptroller. Since PEs fund multiple MDAPs, programs that share a common PE monitor could be isolated. Procurement PEs were not considered for defining funding networks since the RDT&E interdependencies were the most critical to program performance. The funding network and the associated R-docs allowed us to do a detailed study of the performance of the member nodes and to understand the cascading effects. In the future, we plan to apply the lessons learned from this focused study to the entire MDAP network.

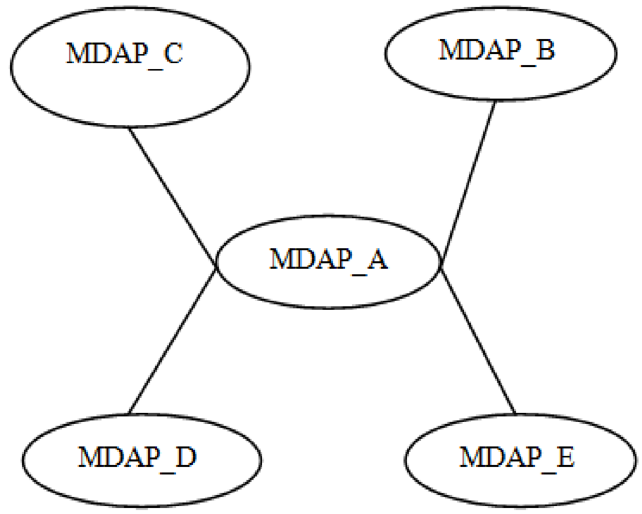

Figure 2. Funding Network of MDAP_A

We analyzed the data that we gathered from the available performance reports of all the MDAPs in the MDAP_A funding network, from local and non-local perspectives, as discussed in the next section. Consider the funding network for MDAP_A in Figure 2. MDAP_A lies at the center of this undirected network that contains five nodes. The link between any two nodes refers to the funding relationship and represents an interdependency between the programs. These links illustrate the interdependent regions of the case study network. We analyzed the performance of the programs based on the APB breaches and amount of increase in %PAUC, which is the percentage change of the current program acquisition unit cost estimate relative to the original APB value. Programs for which the current estimate of PAUC has increased by 15% or more over the currently approved APB must report a unit cost breach to the congressional defense committees. Five types of APB breaches are reported in the performance reports: schedule, performance, RDT&E, procurement, and PAUC. A program is considered to perform poorly if it experiences frequent APB breaches and/or increases in %PAUC.

We note that the central program MDAP_A has been underperforming for a period of time, and we also note that some neighboring programs have been

underperforming in subsequent periods. We want to understand their performance degradation by investigating the following questions:

- Q1: What are the local reasons for a program (e.g., MDAP_A) to underperform?
- Q2: How often and why the forecasting of mitigation efforts, as captured in monthly DAES reports, turns out to be ineffective?
- Q3. What are the non-local reasons for poor performance?
- Q4: How does the effect of one underperforming program propagate through the link towards a neighbor program and affect it?
- Q5: Why is a program that is performing as expected not affected by this perturbation?
- Q6: How does this network-centric approach facilitate the understanding of the underlying problems leading to a cascade in breaches and help the stakeholders to take appropriate measures?

To address the previous questions we employ the following three-phase approach:

Phase 1: Identify programs in the MDAP_A funding network that underperform by analyzing SAR files of all programs, specifically for information pertaining to APB breaches and increases/decreases in %PAUC.

Phase 2: Study the local reasons for the poor performance of the programs based on their respective DAES reports.

Phase 3: Study the non-local reasons for poor performance by analyzing the SAR files.

In the next section, we discuss the details of this three-phase approach.

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III. Phase 1: Identify Programs in the MDAP_A Funding Network That Exhibit Poor Performance

We studied the yearly performance of the MDAP_A funding network using SAR files. Table 1 shows the APB breaches and %PAUC during 2004–2010 for the nodes in the MDAP_A network. Programs initiated after 2004 have data from their respective start date.

Table 1. SAR Summary of the MDAP_A Funding Network for 2004–2010

			APB Breach		
MDAP_A	Schedule	Performance	RDT&E	Procurement	PAUC
2004	None	None	None	None	None (-9.98%)
2005	None	None	None	None	None (-11.65%)
2006	Yes	Yes	Yes	None	None (-6.14%)
2007	None	None	None	None	None (-1.24%)
2009	Yes	None	Yes	None	None (3.14%)
2010	Yes	None	Yes	None	None (3.82%)
MDAP_B					
2004	None	None	None	None	None
2005	Yes	Yes	Yes	None	None (3.85%)
2006	Yes	Yes	Yes	None	None (3.85%)
2007	None	None	None	None	None (7.69%)
2009	Yes	None	None	Yes	None (-26.92%)
2010	Yes	None	Yes	Yes	None (-19.23%)
MDAP_C					
2005	Yes	None	None	None	None (6.51%)
2006	None	Yes	None	None	Yes (13.22%)

2007	Yes	None	None	None	None (0.93%)
2009	Yes	None	None	Yes	None (-37.79%)
2010	Yes	None	None	Yes	None (-26.75%)
MDAP_D					
2009	None	None	None	None	None (2.45%)
2010	Yes	None	None	None	None (1.05%)
MDAP_E					
2006	None	None	None	None	None (-10.685%)
2007	None	None	None	None	None (-4.81%)
2009	None	None	None	None	None (-3.98%)
2010	None	None	None	None	None (-11.24%)

In SAR files, an APB breach is defined as a condition in which the value of the respective breach parameters (schedule, performance, RDT&E, procurement, and PAUC) is in the range of 10–15%, beyond which the condition is defined as a Nunn-McCurdy breach. Table 1 captures whether a program has APB breaches in a given year and what is the %PAUC of that program. A program may have more than one APB breach but experience a decrease in %PAUC. For example, in 2006 the program MDAP_A experienced schedule, RDT&E, and performance breaches, yet its %PAUC decreased. Two possible reasons could account for this fact: (1) the decrease in %PAUC could be due to a lagging effect from the previous year; or/and (2) according to the project management triangle model (Bethke, 2003), program managers may intentionally choose biases towards better performance of one component of the program by trading it off with performance of other components.

Table 1 indicates that in 2004 and 2010 the MDAP_A, MDAP_B, and MDAP_C programs experienced frequent APB breaches and increases in %PAUC. In order to understand the causes of the poor performance for these three programs, we identified the local causes for all five programs and then determined whether interdependency issues existed among them. In other words, we observed whether

any of these poorly performing programs propagated their performance effects to other programs, causing the other programs to perform poorly as well.

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IV. Phase 2: Investigation of Local Reasons for Poor Performance

In this section, we investigate the performance issues local to individual MDAPs and also track how effective “mitigation forecasting” is at resolving pertinent issues. We use the DAES reports of individual programs to analyze their performance from a local perspective. We observe that the DAES reports capture the performance issues of a program’s local domain. We focus on four performances issues recorded in the DAES reports, namely, cost, schedule, performance, and funding.

A. Understanding the Local Causes for MDAP_A to Perform Poorly

We studied a total of 40 DAES reports for MDAP_A that were available from 2006–2010. These reports are published monthly each year, including the election year of 2008, unlike the SAR which did not report in 2008. The program status is presented in DAES reports through the following parameters: cost, schedule, funding, performance, and life-cycle sustainment (see Figure 3). We focus on cost, schedule, performance, and funding parameters. Each parameter reflects both the APB and contract status. The status for each month is represented in one of three colors depending on the severity of the pertinent issue. Green reflects the normal state of meeting all requirements, yellow reflects resolvable issues (Resolvable APB/Contract), and red refers to a state that could not meet the requirements (Critical APB/Contract).

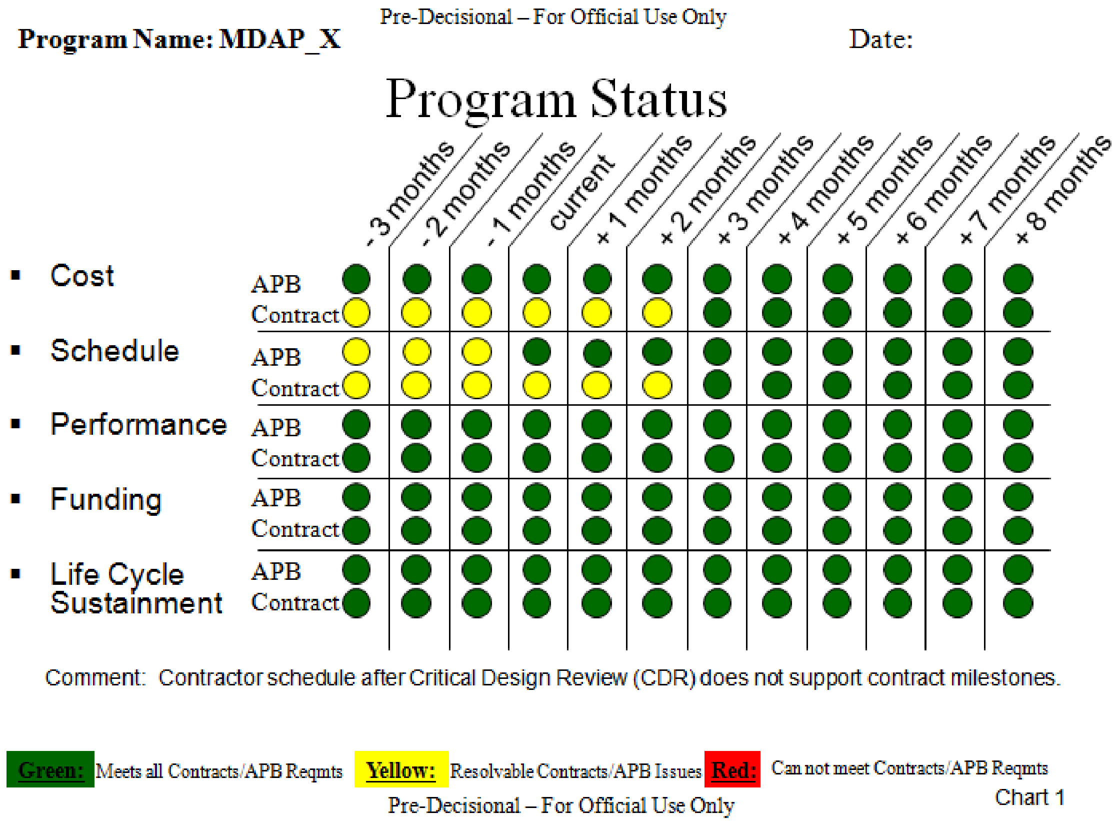

Figure 3. Program Status of MDAP_X

Note. This figure was taken from a DAES report published April 12, 2010, for MDAP_X.

In Figures 4–7, we present a summary of the program status of the DAES reports for MDAP_A in graphical form for the four parameters. The horizontal axis shows the current month while the vertical axis represents the number of months required to resolve an issue (APB or contract) as captured by the DAES reports of the current month. Therefore, these figures illustrate the effectiveness of the forecasting to resolve issues. For example, Figure 3 shows that in April 2007 there were resolvable cost-related APB issues that would take eight months to resolve, but in September 2007 these issues turned critical, which were again forecasted to be resolved in eight months. However, by November 2007, these issues became resolvable and required eight months to be resolved. By June 2008, these issues were finally resolved, but a new resolvable issue emerged that was forecasted to be eliminated in eight months.

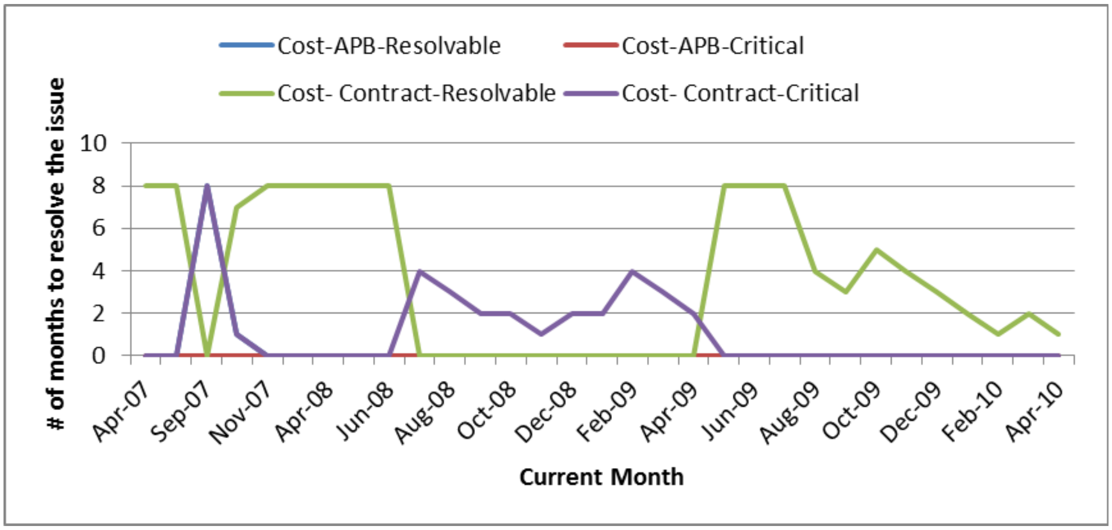

Figure 4. Summary of Cost-Related Issues for MDAP_A From 2007–2010

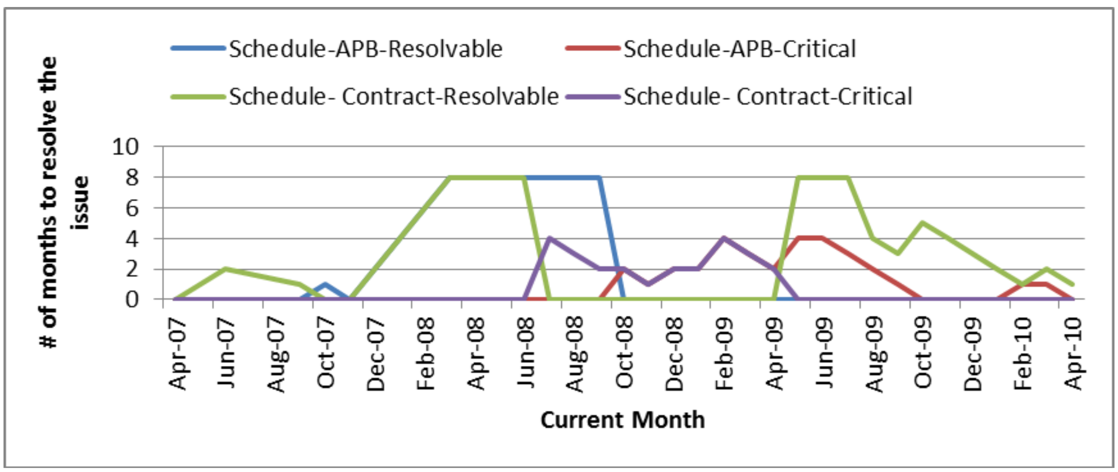

Figure 5. Summary of Schedule-Related Issues for MDAP_A From 2007–2010

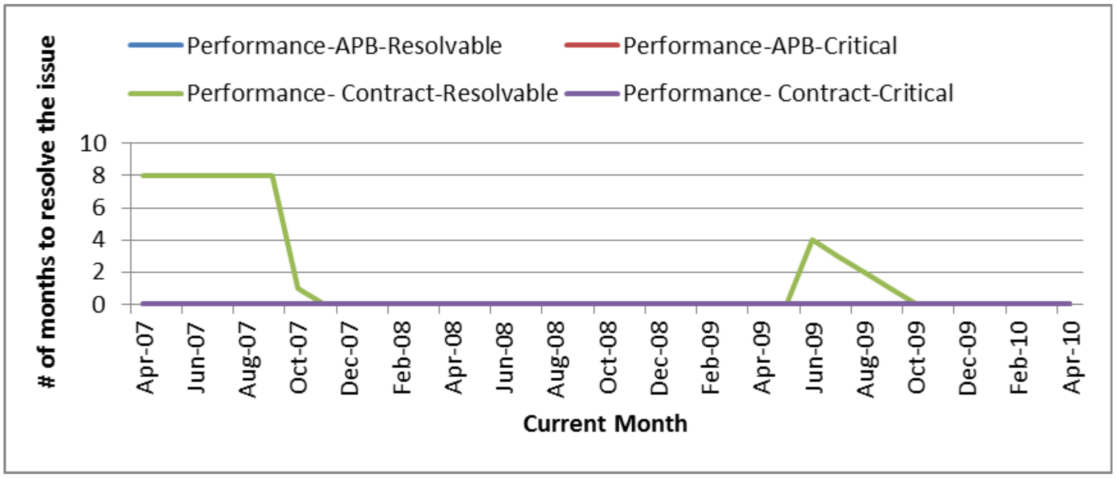

Figure 6. Summary of Performance-Related Issues for MDAP_A From 2007–2010

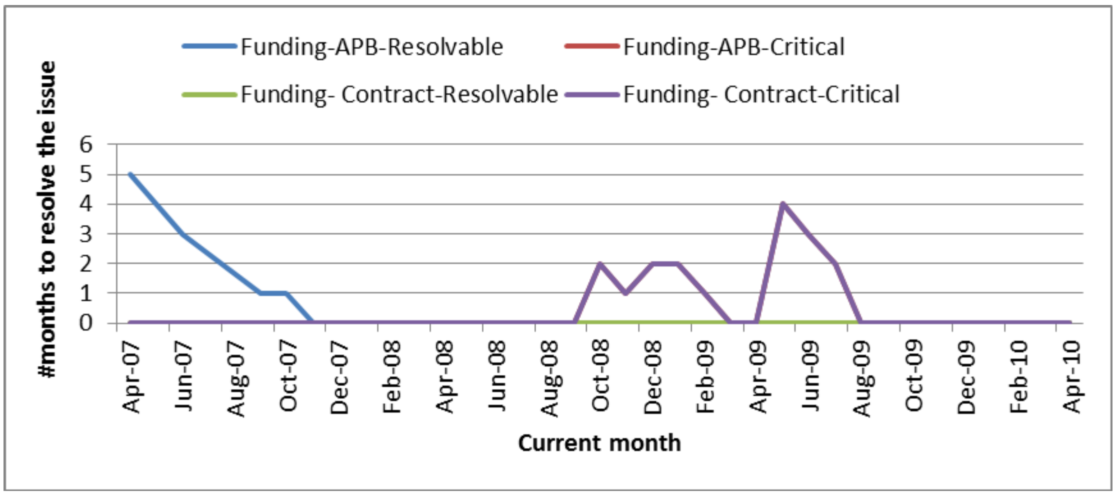

Figure 7. Summary of Funding-Related Issues for MDAP_A From 2007–2010

We first determine how effective APB and contract forecasting are to mitigate the pertinent problems by (a) recording the instances where the forecasting was effective as well as where it was ineffective, and (b) identifying the issues that caused the predictions to slip. We then analyze the issues for deeper understanding and categorization.

In Tables 2–4, we present our analyses in tabular format for three parameters: cost, schedule, and funding. Since MDAP_A did not have any

performance issues, we focus on cost, schedule, and funding issues. For each parameter, we identify the number of issues captured in the respective tables.

1. MDAP_A Cost Analysis

Table 2 captures cost-related issues for the program.

Table 2. MDAP_A Cost Analysis Using DAES Reports From 2006–2010

Current Status	**Status at the Predicted Month**	**Causes**
Month: April 2007 Issue: Contract - Yellow Mitigation Forecast: 8 months	Month: September 2007 Status: Contract - Red Note: After 5 months the contract issue turns into critical	**Issue 1:** hardware building **Issue 2:** hardware design **Issue 3:** logistics issue
Month: September 2007: Issue: Contract - Red APB - Yellow Mitigation Forecast: 8 months	Month: June 2008 Status: Contract - Yellow APB – Green	**Issues 1–3:** resolved **Issue 4:** Contractor unable to forecast cost.
Month: June 2008 Issue: Contract - Yellow Mitigation Forecast: 8 months	Month: July 2008 Status: Contract - Red Note: After 1 month the contract issue turns into critical	**Issue 4:** Contractor unable to forecast cost. **Issue 5:** Schedule delay increased contract cost.
Month: July 2008 Issue: Contract - Red Mitigation Forecast: 4 months	Month: December 2008 Status: Contract - Red	**Issue 4:** Contractor unable to forecast cost. **Issue 5:** Schedule delay increased contract cost.
Month: December 2008 Issue: Contract - Red Mitigation Forecast: 2 months	Month: March 2009 Status: Contract - Red	**Issue 4:** Contractor unable to forecast cost. **Issue 5:** Schedule delay increased contract cost.
Month: March 2009 Issue: Contract - Red Mitigation Forecast: 3 months	Month: July 2009 Status: Contract - Yellow	**Issue 4:** remains **Issue 5:** remains
Month: July 2009 Issue: Contract - Yellow Mitigation Forecast: 8 months	Month: April 2010 Status: Contract - Yellow	**Issue 4:** remains **Issue 5:** remains

Lessons Learned: Although Table 2 suggests that there are some instances where the forecasting turned out to be effective, we observe and focus on the

instances where cost-related forecasting was ineffective. We identify two local issues, namely (1) contractors' inability to forecast cost; and (2) schedule delays leading to increased contract cost, which appear to recur and lead to increased program costs.

2. MDAP_A Schedule Analysis

Table 3 captures schedule-related issues for the program.

Table 3. MDAP_A Schedule Analysis Using DAES Reports From 2006–2010

Current Status	**Status at the Predicted Month**	**Causes**
Month: June 2007 Issue: Contract - Yellow Mitigation Forecast: 2 months	Month: September 2007 Status: Contract - Yellow Note: August 2007 report is not available.	**Issue 1:** Delay in MOU sign with Australia.
Month: September 2007 Issue: Contract - Yellow Mitigation Forecast: 1 month	Month: October 2007 Status: Contract - Green	**Issue 1:** remains **Issue 2:** Software testing, delivery, and other waveform issues
Month: October 2007 Issue: APB - Yellow Mitigation Forecast: 1 month	Month: November 2008 Status: APB - Green	**Issue 1:** resolved **Issue 2:** resolved
Month: March 2008 Issue: APB - Yellow Contract - Yellow Mitigation Forecast: 8 months	Month: November 2008 Status: APB - Red Contract - Red	**Issue 3:** Hardware testing and performance failure **Issue 4:** Execution delay in contractor's schedule & lack in funding
Month: November 2008 Issue: APB - Red Contract - Red Mitigation Forecast: 2 months	Month: December 2008 Status: APB - Red Contract - Red	**Issue 3:** Hardware testing and performance failure **Issue 4:** Execution delay in contractor's schedule & lack in funding
Month: December 2008 Issue: APB - Red Contract - Red Mitigation Forecast: 2 months	Month: February 2009 Issue: APB - Red Contract - Red Mitigation Forecast: 2 months	**Issue 3:** Hardware testing and performance failure **Issue 4:** Execution delay in contractor's schedule & lack in funding

Month: February 2009 Issue: APB - Red Contract - Red Mitigation Forecast: 4 months	Month: June 2009 Status: APB - Red Contract - Red	**Issue 4:** Execution delay in contractor's schedule & lack in funding **Issue 3:** Hardware testing and performance failure
Month: June 2009 Issue: APB - Red Contract - Yellow Mitigation Forecast: APB: 4 months Contract: 8 months	Month: October 2009 Status: APB - Green Contract - Yellow	
Month: October 2009 Issue: Contract - Yellow Mitigation Forecast: Contract: 5 months	Month: March 2010 Status: APB - Red Contract - Yellow	**Issue 4:** Execution delay in contractor's schedule & lack in funding **Issue 3:** Hardware testing and performance failure

Lessons Learned: Although there are some instances for which the forecasting turned out to be effective, we observe and focus on the instances where schedule-related forecasting was ineffective. We identify two local issues, namely (1) hardware testing and performance failure and (2) execution delay and lack of funding, which appear to recur and lead the program towards schedule delay.

3. MDAP_A Funding Analysis

Table 4 captures funding-related issues for the program.

Table 4. MDAP_A Funding Analysis Using DAES Reports From 2006–2010

Current Status	**Status at the Predicted Month**	**Causes**
Month: April 2007 Issue: APB - Yellow Mitigation Forecast: Contract: 5 months	Month: September 2007 Status: APB - Yellow	**Issue 1:** WPN Fund cut
Month: September 2007 Issue: APB - Yellow Mitigation Forecast: Contract: 1 month	Month: October 2007 Status: APB - Yellow	**Issue 1:** WPN Fund cut
Month: October 2008 Issue: APB - Red Contract - Red Mitigation Forecast: APB: 4 months Contract: 2 months	Month: December 2008 Status: APB - Red Contract - Red	**Issue 1:** WPN Fund cut
Month: December 2008 Issue: APB - Red Contract - Red Mitigation Forecast: APB: 4 months Contract: 2 months	Month: February 2009 Status: APB - Red Contract - Red	**Issue 1:** WPN Fund cut
Month: February 2009 Issue: APB - Red Contract - Red Mitigation Forecast: APB: 1 month Contract: 1 month	Month: March 2009 Status: APB - Green Contract - Green	
Month: April 2009 Issue: APB - Red Contract - Red Mitigation Forecast: By the current month	Month: May 2009 Status: APB - Red Contract - Red	**Issue 1:** WPN Fund cut
Month: May 2009 Issue: APB - Red Contract - Red Mitigation Forecast: 4 months	Month: September 2009 Status: APB - Green Contract - Green	

Lessons Learned: Although there are some instances for which the forecasting turned out to be effective, we observe and focus on the instances where

funding-related forecasting was ineffective. We identify one local issue, namely the Weapons Procurement Cut, that appears to recur and lead the program to experience funding-related problems (for example, lack of funding caused a schedule delay, as captured in the MDAP_A schedule analyses).

Based on these lessons from the cost, schedule, and funding analyses of MDAP_A, we identify the following observations that appear to be responsible for the APB cost and schedule breach of MDAP_A:

Observation 1: The design of MDAP_A relies on cutting-edge technology. It seems that the contractor underestimated or could not accurately estimate the technical challenges and the amount of funding required to accomplish the tasks.

Observation 2: MDAP_A suffered greatly due to budget cuts. The program did not receive the required amount of funding from the government (congressional committee), which delayed the schedule and, as a consequence, cost increased.

B. Understanding the Local Causes for MDAP_B to Perform Poorly

In this section, we describe the analysis of 44 DAES reports for MDAP_B that were available from 2006–2010. We first determined the effectiveness of APB and contract forecasting to mitigate the pertinent problems. We did this by recording the instances when the forecasting was effective as well as when it was ineffective. We then sought to identify and analyze the issues that caused the predictions to slip.

In Figures 8–11, we present a summary of the DAES reports for MDAP_B in graphical form for the four parameters.

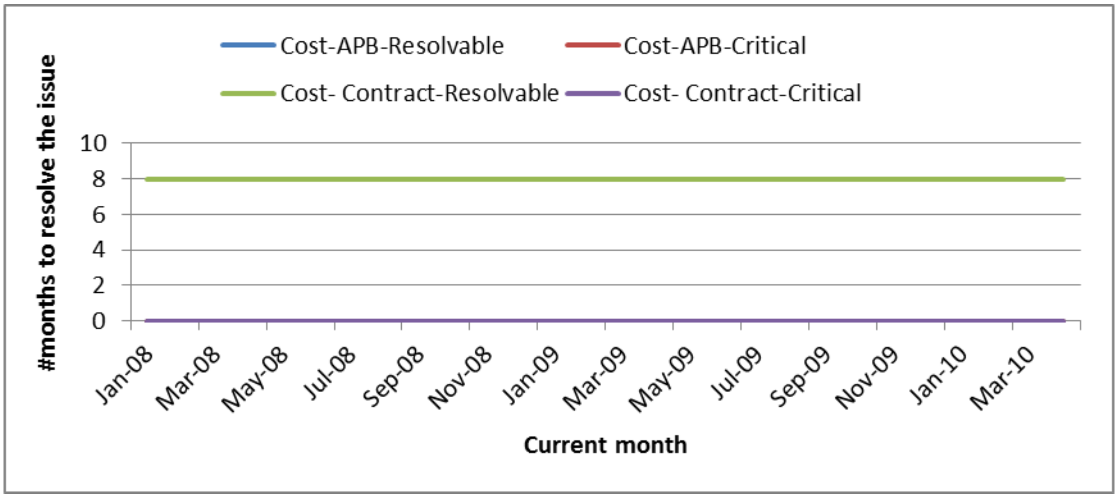

Figure 8. Summary of Cost-Related Issues for MDAP_B From 2008–2010

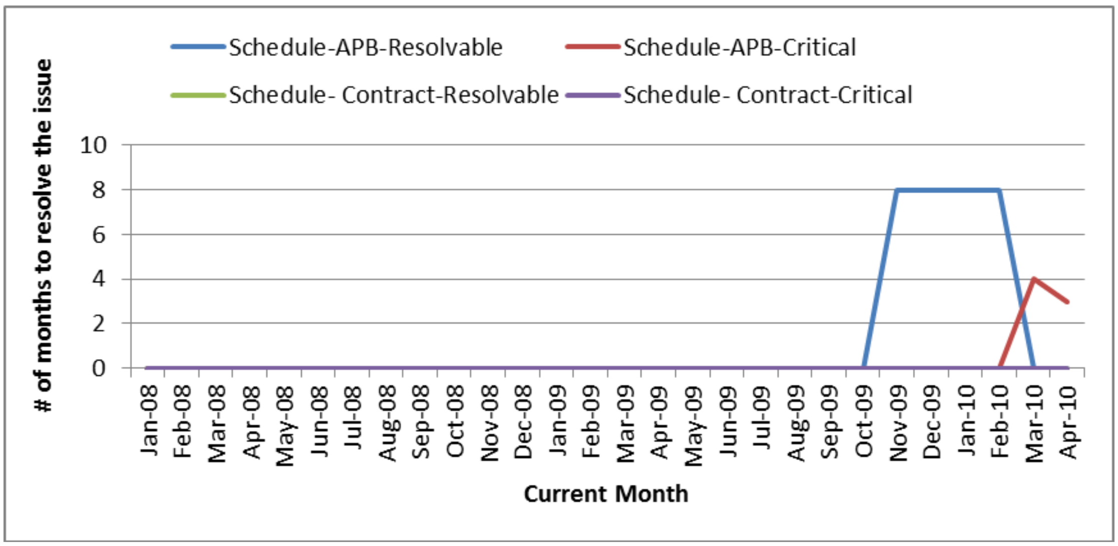

Figure 9. Summary of Schedule-Related Issues for MDAP_B From 2008–2010

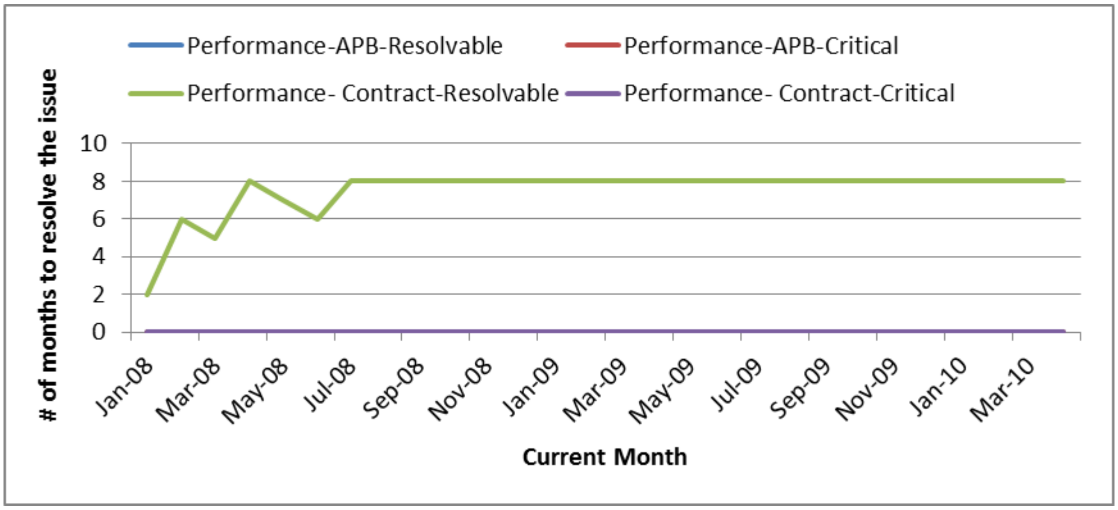

Figure 10. Summary of Performance-Related Issues for MDAP_B From 2008–2010

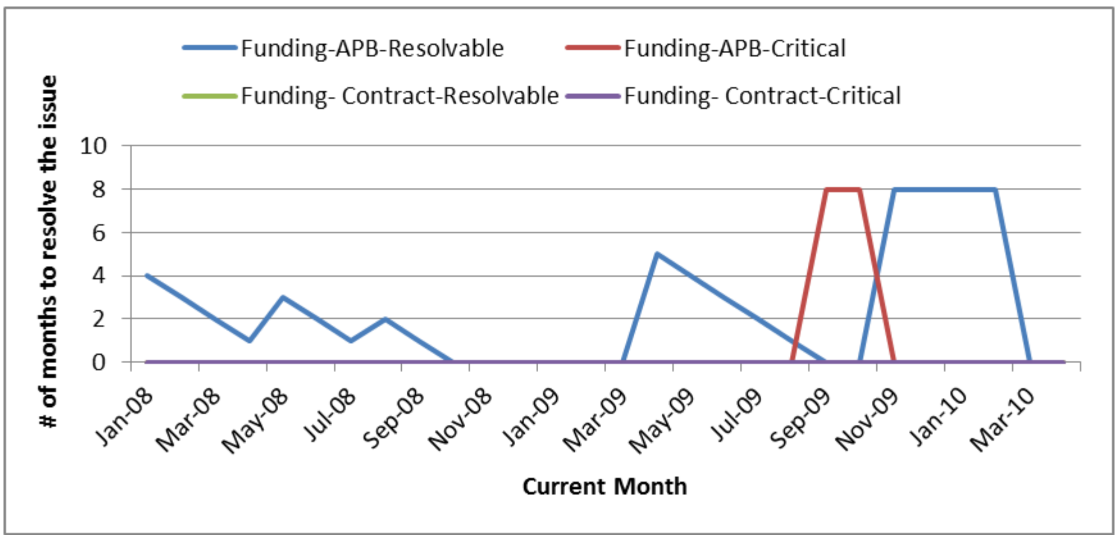

Figure 11. Summary of Funding-Related Issues for MDAP_B From 2008–2010

We present our analyses in Tables 5–7 for three parameters: cost, schedule, and funding. Since MDAP_B did not have any performance issues, we focus on cost, schedule, and funding issues.

1. MDAP_B Cost Analysis

Table 5 captures cost-related issues for the program.

Table 5. MDAP_B Cost Analysis Using DAES Reports From 2006–2010

Current Status	Status at the Predicted M11onth	Causes
Month: February 2007 Issue: APB - Yellow Mitigation Forecast: 3 months	Month: May 2007 Status: APB - Yellow	**Issue 1:** require procurement funding
Month: May 2007 Issue: APB - Yellow Mitigation Forecast: 1 month	Month: June 2007 Status: APB - Yellow	**Issue 1:** require procurement funding
Month: June 2007 Issue: APB - Yellow Mitigation Forecast: 2 months	Month: August 2007 Status: APB - Yellow	**Issue 1:** require procurement funding **Issue 2:** contractor cost increased
Month: August 2007 Issue: APB - Yellow Contract - Yellow Mitigation Forecast: 1 month	Month: September 2007 Status: APB - Yellow Contract - Yellow	**Issue 1:** require procurement funding **Issue 2:** contractor cost increased
Month: September 2007 Issue: APB - Yellow Contract - Yellow Mitigation Forecast: APB: 1 month Contractor: 8 months	Month: October 2007 Status: APB - Green Contract - Yellow	**Issue 1:** require procurement funding **Issue 2:** contractor cost increased
Month: October 2007 Issue: Contract - Yellow Mitigation Forecast: 8 months	Month: June 2008 Status: Contract - Yellow	**Issue 1:** require procurement funding **Issue 2:** contractor cost increased
Month: June 2008 Issue: Contract - Yellow Mitigation Forecast: 8 months	Month: February 2009 Status: Contract - Yellow	**Issue 1:** require procurement funding **Issue 2:** contractor cost increased
Month: February 2009 Issue: Contract - Yellow Mitigation Forecast: 8 months	Month: October 2009 Status: Contract - Yellow	**Issue 1:** require procurement funding **Issue 2:** contractor cost increased
Month: October 2009 Issue: Contract - Yellow Mitigation Forecast: 8 months	Month: April 2010 Status: Contract - Yellow Note: No data available beyond April 2010	**Issue 1:** require procurement funding **Issue 2:** contractor cost increased

Lessons Learned: Although there are some instances for which the forecasting turned out to be effective, we observe and focus on the instances where cost-related forecasting was ineffective. We identify two local issues, namely (1) lack in procurement funding and (2) increased contract cost, which appear to recur and lead the program towards cost increase.

2. MDAP_B Schedule Analysis

Table 6 captures schedule issues for the program.

Table 6. MDAP_B Schedule Analysis Using DAES Reports From 2006–2010

Forecasting	Status at the Predicted Month	Causes
Month: September 2006 Issue: APB - Yellow Mitigation Forecast: 6 months	Month: March 2007 Status: APB - Yellow	None identified
Month: March 2007 Issue: APB - Yellow Mitigation Forecast: 2 months	Month: May 2007 Status: APB - Yellow	None identified
Month: May 2007 Issue: APB - Yellow Mitigation Forecast: 1 month	Month: June 2007 Status: APB	None identified
Month: June 2007 Issue: APB - Yellow Mitigation Forecast: 2 months	Month: August 2007 Status: APB - Yellow	None identified
Month: August 2007 Issue: APB - Yellow Mitigation Forecast: 1 month	Month: September 2007 Status: APB - Yellow	None identified
Month: September 2007 Issue: APB - Yellow Mitigation Forecast: 2 months	Month: November 2007 Status: APB - Green	None identified

Month: November 2010 Issue: APB - Yellow Mitigation Forecast: 5 months	Month: April 2010 Status: APB - Red Note: No data available beyond April 2010	**<u>Issue 2:</u>** Phase 1 Milestone C decision date postponement and potential to move right beyond threshold date. An MS C Threshold Breach causes the Phase 1 (External Program) to be red for +3 months

Lessons Learned: Although there are some instances for which the forecasting turned out to be effective, we observe and focus on the instances where schedule-related forecasting was ineffective. The DAES reports did not however capture the reasons for MDAP_B's schedule delay.

3. MDAP_B Funding Analysis

Table 7 captures funding-related issues for the program.

Table 7. MDAP_B Funding Analysis Using DAES Reports From 2006–2010

Forecasting	Status at the Predicted Month	Causes
Month: February 2007 Issue: APB - Yellow Contract - Yellow Mitigation Forecast: 3 months	Month: May 2007 Status: APB - Yellow Contract - Yellow	**<u>Issue 1:</u>** require procurement funding
Month: May 2007 Issue: APB - Yellow Contract - Yellow Mitigation Forecast: 1 month	Month: June 2007 Status: APB - Yellow Contract - Yellow	**<u>Issue 1:</u>** require procurement funding
Month: June 2007 Issue: APB - Yellow Contract - Yellow Mitigation Forecast: 2 months	Month: August 2007 Status: APB - Yellow Contract - Yellow	**<u>Issue 1:</u>** require procurement funding
Month: August 2007 Issue: APB - Yellow Contract - Yellow Mitigation Forecast: 1 month	Month: September 2007 Status: APB - Green Contract - Green	None identified

Month: March 2008 Issue: APB - Yellow Mitigation Forecast: 4 months	Month: July 2008 Status: APB - Yellow	**Issue 1:** require procurement funding
Month: July 2008 Issue: APB - Yellow Mitigation Forecast: 3 months	Month: October 2008 Status: APB - Yellow	**Issue 1:** require procurement funding
Month: October 2008 Issue: APB - Yellow Mitigation Forecast: 3 months	Month: January 2009 Status: APB - Yellow	**Issue 1:** require procurement funding
Month: January 2009 Issue: APB - Yellow Mitigation Forecast: current month	Month: February 2009 Status: APB - Yellow	**Issue 1:** require procurement funding
Month: February 2009 Issue: APB - Yellow Mitigation Forecast: current month	Month: March 2009 Status: APB - Green	None identified
Month: June 2009 Issue: APB - Yellow Mitigation Forecast: 5 months	Month: November 2009 Status: APB - Red	**Issue 2:** R&D shortfall driven by overall technical and schedule issues **Issue 3:** Hardware testing issue to increase program cost
Month: November 2009 Issue: APB - Red Mitigation Forecast: 8 months	Month: April 2010 Status: APB - Red Note: No data available beyond April 2010	**Issue 2:** FY 12–15 R&D shortfall driven by overall technical and schedule issues **Issue 3:** Hardware testing issue to increase program cost

Lessons Learned: Although there are some instances for which the forecasting turned out to be effective, we observe and focus on the instances where funding-related forecasting was ineffective. We identify three local issues, namely (1) lack of required procurement funding, (2) an R&D shortfall driven by overall technical and schedule issues, and (3) a hardware testing issue that increased program cost. These issues appear to recur and lead the program towards experiencing funding-

related problems (for example, a cost increase as captured in the MDAP_B cost analyses).

Based on these lessons learned from the cost, schedule, and funding analyses of MDAP_B, we make the following observations about what is responsible for the APB cost and schedule breach of MDAP_B:

Observation 3: A lack in procurement funding is the most beleaguering issue for MDAP_B's observed cost and funding problems.

Observation 4: The above DAES report-based analyses presented in Tables 5-7 , however, do not provide any clue as to why the shortfall in funding. This underscores the importance of looking beyond the local view of a program and of searching for non-local causes that could have contributed to the degradation in performance. This motivates us to investigate the interdependent region between MDAP_A and MDAP_B to identify possible cascading effects.

C. Understanding Local Issues of MDAP_C

We studied a total of 46 DAES reports for MDAP_C that were available from 2006–2010. In this section, we evaluate the effectiveness of APB and contract forecasting to mitigate the pertinent problems. To do this, we recorded the instances when the forecasting was effective as well as when it was ineffective. We then identified and analyzed the issues that caused the predictions to slip.

We present our analyses in Tables 8–10 for three parameters: cost, schedule, and funding. Since MDAP_C did not have any performance issues, we focus on the cost, schedule, and funding issues.

1. MDAP_C Cost Analysis

Table 8 captures cost-related issues for the program.

Table 8. MDAP_C Cost Analysis Using DAES Reports From 2006–2010

Current Status	Status at the Predicted Month	Causes
Month: March 2007 Issue: APB - Red Mitigation Forecast: current month	Month: April 2007 Status: APB - Red	**Issue 1:** FY08 PB caused an APB cost breach in the PAUC.
Month: April 2007 Issue: APB - Red Mitigation Forecast: 8 months	Month: December 2007 Status: APB - Green	Note: Issue 1 resolved due to approved baseline.

Lessons Learned: We did not observe any noticeable cost-related issue.

2. MDAP_C Schedule Analysis

Table 9 captures schedule issues for the program.

Table 9. MDAP_C Schedule Analysis Using DAES Reports From 2006–2010

Current Status	Status at the Predicted Month	Causes
Month: March 2007 Issue: APB - Yellow Mitigation Forecast: current month	Month: April 2007 Status: APB - Green	None identified
Month: July 2007 Issue: Contract - Yellow Mitigation Forecast: 8 months	Month: March 2008 Status: Contract - Yellow	**Issue 1:** Contract Schedule is yellow due to IDIQ Production and Production facility transition contract award, expected 1st Qtr & 2nd Qtr FY09, respectively.
Month: October 2007 Issue: APB - Yellow Mitigation Forecast: 8 months	Month: December 2007 Status: APB - Red	**Issue 2:** The slip in the release of the MOT&E-2 report could potentially delay the IOC-2/3 decision and cause an APB breach.
Month: December 2007 Issue: APB - Red Mitigation Forecast: 2 months	Month: February 2008 Status: APB - Red	**Issue 2:** APB schedule is red because the slip in the release of the MOT&E-2 report delayed the IOC-2/3 decision past the 31 Dec 07 APB threshold, which resulted in an APB breach.
Month: February 2008 Issue: APB - Red	Month: June 2008 Status: APB - Red	**Issue 2:** APB schedule is red because the slip in the

Mitigation Forecast: 4 months		release of the MOT&E-2 report delayed the IOC-2/3 decision past the 31 Dec 07 APB threshold, which resulted in an APB breach.
Month: March 2008 Issue: Contract - Yellow Mitigation Forecast: 8 months	Month: November 2008 Status: Contract - Green	None identified
Month: June 2008 Issue: APB - Red Mitigation Forecast: 1 month	Month: July 2008 Status: APB - Red	**Issue 2:** IOC 2/3 current estimate of 30 Jun 08 has slipped to Oct 08 due to Joint Staff critical comments.
Month: July 2008 Issue: APB - Red Mitigation Forecast: 3 months	Month: November 2008 Status: APB - Green	None identified

Lessons Learned: The only issue that affected the schedule is the following: Completion of the Initial Operational Capability (IOC) 2/3 milestone was delayed because of changes in reporting procedures and evaluation criteria at the operational test agency while this milestone was under evaluation. As a result, the final multi-service Operational Test and Evaluation or MOT&E-2 report from AFOTEC was delayed.

3. MDAP_C Funding Analysis

Table 10 captures funding-related issues for the program.

Table 10. MDAP_C Funding Analysis Using DAES Reports From 2006–2010

Current Status	Status at the Predicted Month	Causes
Month: March 2008 Issue: Contract - Yellow Mitigation Forecast: 8 months	Month: December 2008 Status: Contract - Green	None identified
Month: January 2009 Issue: Contract - Yellow Mitigation Forecast: 8 months	Month: October 2009 Status: Contract - Yellow	None identified
Month: October 2009 Issue: Contract - Yellow Mitigation Forecast: 8 months	Month: April 2009 Status: Contract - Yellow	None identified

Lessons Learned: We cannot find any significant information on the funding issues from the DAES reports on MDAP_C.

D. Understanding Local Issues of MDAP_D

We studied a total of 24 DAES reports for MDAP_D available from 2008–2010. We first determined the effectiveness of APB and contract forecasting to mitigate the pertinent problems. To do this, we recorded the instances when the forecasting was effective as well as when it was ineffective. We then identified and analyzed the issues that caused the predictions to slip.

We present our analyses in Tables 11 and 12 for two parameters: cost and schedule. Since MDAP_D did not have any funding- or performance-related issues, we focus on the cost and schedule issues.

1. MDAP_D Cost Analysis

Table 11 captures cost-related issues for the program.

Table 11. MDAP_D Cost Analysis Using DAES Reports From 2008–2010

Current Status	Status at the Predicted Month	Causes
Month: May 2009 Issue: Contract - Yellow Mitigation Forecast: 8 months	Month: November 2009 Status: Contract - Yellow	None identified
Month: November 2009 Issue: Contract - Yellow Mitigation Forecast: 2 months	Month: January 2010 Status: Contract - Green	None identified
Month: January 2010 Issue: Contract - Yellow Mitigation Forecast: 4 months	Month: April 2010 Status: Contract - Yellow	None identified

Lessons Learned: We did not observe any cost-related issue.

2. MDAP_D Schedule Analysis

Table 12 captures schedule issues for the program.

Table 12. MDAP_D Schedule Analysis Using DAES Reports From 2008–2010

Current Status	Status at the Predicted Month	Causes
Month: April 2009 Issue: Contract - Yellow Mitigation Forecast: 1 month	Month: May 2009 Status: Contract - Yellow	**Issue 1:** The Critical Design Review (CDR) date is expected to move to Sep 09 in order to accommodate Joint Industry/Government Tiger Team recommendations to reduce Information Assurance certification issues. **Issue 2:** The contractor schedule may not support testing required to satisfy exit criteria to meet the MSC objective date of Nov 2011.
Month: May 2009 Issue: Contract - Yellow Mitigation Forecast: 5 months	Month: October 2009 Status: Contract - Yellow APB - Yellow	**Issue 1:** remains **Issue 2:** remains
Month: October 2009 Issue: APB - Yellow Contract - Yellow Mitigation Forecast: 3 months	Month: January 2010 Status: Contract - Yellow	**Issue 2:** remains **Issue 3:** Potential impact to program schedule as a result of concurrent software and hardware development interdependencies.
Month: January 2010 Issue: Contract - Yellow Mitigation Forecast: 4 months	Month: April 2010 Status: Contract - Yellow	**Issue 2:** resolved. **Issue 3:** Potential impact to program schedule as a result of concurrent software and hardware development interdependencies.

Lessons Learned: We identify that concurrent waveform and hardware development interdependencies may have affected the program schedule.

E. Understanding Local Issues of MDAP_E

We studied a total of 41 DAES reports for MDAP_E that were available from 2007–2010. We first determined the effectiveness of APB and contract forecasting to mitigate the pertinent problems. To do this, we recorded the instances when the

forecasting was effective as well as when it was ineffective. We then identified and analyzed the issues that caused the predictions to slip.

We cannot, however, find significant degradation in terms of cost-, schedule-, funding-, and performance-related issues for MDAP_E.

The above DAES report-based analyses presented in Tables 8-12 indicate that MDAP_C, MDAP_D, and MDAP_E may not have affected the performance of MDAP_A and it appears that there could be potential interdependency between MDAP_A and MDAP_B. We, therefore, compare and investigate the issues related to these two programs in an effort to better understand the possible interdependencies.

In Table 13, we provide a summary of findings revealed from the study of DAES reports for MDAP_A and MDAP_B, in an effort to understand the non-local issues.

Table 13. MDAP_A and MDAP_B Local Issue Summary for 2006–2010

MDAP_A Issues	**MDAP_B Issues**
- Contractor's inability to forecast cost - Schedule delay increased contract cost - Hardware testing and performance failure - Execution delay and lack of funding	- Lack in procurement funding - Increased contract cost - Required procurement funding - R&D shortfall driven by overall technical and schedule issues - Hardware testing issue to increase program cost

Table 13 indicates that although the contractor's ineffective forecasting and schedule delay (due to hardware and design issues) led MDAP_A to incur a cost overrun, the lack in procurement funding appears to be the plaguing issue for the increase in cost of MDAP_B. Based on this observation, we propound the following hypothesis: The cost increase of MDAP_A in 2009 could have caused the procurement funding shortfall for MDAP_B in 2010, which, in effect, increased the cost of MDAP_B (as the DAES reports on MDAP_B suggest).

This hypothesis indicates that the cost increase of MDAP_A (in 2009) is due to non-local reasons. DAES reports do not provide enough insight about interdependency regions and, hence, we could not capture the non-local causes from these reports. However, we observe that the SAR files to some extent offer a better perspective to understand the interdependency region. In the following section, we provide a comparative analysis of the funding phenomena for these two programs in an effort to discover interdependency between the cost increase problem of MDAP_A and funding shortfall of MDAP_B.

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V. Phase 3: Study of the Non-Local Reasons for Poor Performance by Analyzing the SAR

To verify the hypothesis of interdependency, we created Tables 14 and 15, which contain the funding summary (based on base year dollar) from the SAR files of MDAP_A and MDAP_B for the period 2004–2010. Our study indicates that comparative analyses of SAR files for the programs in MDAP_A's funding network provide insight about the joint space and, hence, are useful for us to identify non-local issues. SAR captures the yearly APB breach status, %PAUC, cost, and funding data; hence, it is suitable for quantitative analyses.

Table 14. MDAP_A SAR Funding Summary ($BY) for the Period 2004–2010

MDAP_A	**Baseline** Quantity	**Current** Quantity	**%PAUC**	**Current Year** Required Funding (x)	**Received Funding** (y)	**Delta** (y - x)
2004	6	6	-9.98		221.1	
2005	6	6	-11.65	598.5	579.8	-18.7
2006	6	6	-6.14	1012.1	997.3	-14.8
2007	6	6	-1.24	1588.4	1574.6	-13.8
2009	6	6	3.14	3163.2	3006.3	-156.9
2010	6	6	3.82	3750.7	3813.2	62.5

Table 15. MDAP_B SAR Funding Summary ($BY) for the Period 2004–2010

MDAP_B	**Baseline** Quantity	**Current** Quantity	**%PAUC**	**Current Year** Required Funding (x)	**Received Funding** (y)	**Delta** (y - x)
2004	329574	329574	0	44.2	44.2	0
2005	329574	328514	3.85	137.2	135.5	-1.7
2006	329574	328514	3.85	255.5	250.3	-5.2
2007	329574	95961	7.69	350.5	348.1	-2.4
2009	329574	215961	-26.92	644.1	593.2	-50.9
2010	329574	221978	-19.23	751.6	711.1	-40.5

In Tables 14 and 15, we focus on the parameter “delta,” which captures the difference in the amount of required and received funding for the respective year. For MDAP_A, we notice that from 2009–2010 the %PAUC increased while delta turned out to be positive. On the other hand, for MDAP_B from 2009–2010, delta retained a large negative value even though, given the trends over the years, the increase in quantity (~4000 units) was not large enough to justify this increase. Both the DAES and SAR files of MDAP_B do not provide reasons for the large negative value of delta in 2009 and 2010. We suspect that the cost overrun of MDAP_A from 2009 onward might have affected MDAP_B in 2010 through a procurement funding shortfall. This observation, even if it may not be conclusive, is suggestive of cascading effects between neighboring MDAPs. We believe that a thorough study of the entire set of MDAPs may enable us to find more interesting interdependencies and would be able to predict the flow of the cascading effects.

VI. Observations From the Performance Reports-Based Analyses

We studied the DAES and SAR files of MDAP_A and MDAP_B available from 2006–2010 in an effort to identify a cascading effect in the MDAP_A funding network. We tried to understand the local as well as non-local issues that led the programs towards breach condition. The following are the summary of observations from this process.

Observation 1: The design of MDAPs relies on cutting-edge technology. It appears that the contractor either underestimates or cannot accurately estimate the technical challenges and the amount of funding required to accomplish the tasks.

Observation 2: Programs are affected greatly by budget cuts. Sometimes a program does not receive the required amount of funding from the government (congressional committee), which delays the schedule, and, as a consequence, cost increases.

Observation 3: Lack in procurement funding is another cause that leads to cost and funding problems.

Observation 4: Analyses of the local issues and the fact that some of the issues are recurrent indicate that either the root cause of the problem is not captured in the DAES documents or that the cause is exogenous to the program boundary.

Observation 5: Analyses of SAR files, on the other hand, offer some insight about the interdependency of the programs.

Observation 6: The observed instance of a possible cascading effect in the MDAP_A network motivates us to design an automated scheme that would be able to identify and predict the likelihood of cascading effects.

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VII. Progress Towards a Decision-Theoretic Model for the MDAP Network

In this section, we describe our initial work in determining whether a decision-theoretic model for probabilistic analysis of decisions is feasible given the data we have available about the MDAP case study network. Our goal is do a small-scale feasibility study in this project and leave the implementation of the model to future work where we expect to have access to larger amounts of data, which are crucial for accurate modeling and analysis.

A Markov Decision Process (MDP; Bertsekas, 1987) is a probabilistic model for decision-making and planning. It uses dynamic programming to decide on the optimal actions (in this case, cut funding by 50% or delay schedule by six months) that yields the highest expected utility (for example, no PAUC growth or no APB breaches). MDPs capture the essence of sequential processes and are used to compute *decision* policies that lead to the best long-term performance for the entire network.

In theory, MDPs implement two forms of hedging that can allow managers to (1) test their decisions to avoid the possibility of failure and (2) choose actions that ensure higher overall expected reward. These hedging strategies alter expectations about future problem occurrences in a manner that allows managers to shift behaviors to improve performance.

In our approach, MDAPs are considered as individual agents that are part of a cooperative multiagent system, and decision-making in an MDAP network is viewed as a multiagent sequential decision problem because the utility gained by each agent depends on a sequence of actions over time. Our goal is to determine the behavior of the agents that best balances the risks and rewards while acting in an uncertain environment with stochastic actions.

Each MDAP makes its individual decisions in an environment where the state space is not fully observable, meaning that the nodes in the network (the programs) do not exactly know which state they are in at any particular instant because they do not have complete information about their neighbors. With the partial state information, the individual agents aim to optimize the joint reward function. This class of problems is modeled as decentralized partially observable MDP (DEC-POMDP) in the literature (Bernstein et al., 2002) where at each step when an agent takes an action, a state transition occurs and the agent receives a local observation. Following this, the environment generates a global reward that depends on the set of actions taken by all the agents. The complexity, however, of this decentralized control model is NEXP-hard (Bernstein et al., 2002) and, hence, it is computationally intractable. In our previous work (Cheng, Raja, & Lesser, 2012), we make the DEC-POMDP problem for tornado tracking tractable by approximating the DEC-POMDP with a stochastic DEC-MDP[1] model and using a factored reward function to define a Nash Equilibrium instead of the global reward function. A necessary condition for stable equilibrium among agents in a multiagent system is that each agent plays a best-response to the strategy of every other agent: This is called a Nash Equilibrium. We apply this technique to the MDAP domain. We define the reward function of this model to be composed of two different components: local reward function and global reward function. The local reward functions are dependent only on the individual agents' actions, while the global reward function depends on the action of all agents. Stochastic models are known to cope with the uncertainty of observation and perform better than deterministic policies in a partially observable environment.

The stochastic DEC-MDP model is formally defined as a tuple $<\mathcal{S}, \mathcal{A}, \mathcal{T}, \mathcal{R}>$, where $\mathcal{S} = S_1 \, x \, S_2 \, x \ldots\ldots \, x \, S_n$ is a finite set of factored world states, and where S_i is the state space of agent *i*. Also, $\mathcal{A} = A_1 \, x \, A_2 \, x \ldots . x \, A_n$ is a finite set of joint actions, where A_i is the action set for agent *i*.

[1] A DEC-MDP is a DEC-POMDP with joint full observability (Bernstein et al., 2002).

$\mathcal{T}: \mathcal{S} \times \mathcal{A} \times \mathcal{S} \rightarrow \mathbb{R}$ is the transition function. $T(s' \mid s, a)$ is the probability of transiting to the next state after a joint action $a \in A$ is taken by agents in state s.

$\mathcal{R} = \{R_1, R_2, \ldots, R_n\}$ is a set of factored reward functions. $R_i : S \times A \rightarrow \mathbb{R}$ provides agent i with an individual reward $r_i \in R_i(s, a)$ for taking action a in state s.

A stochastic policy of an agent i is denoted by $\Pi_i(s) \in PD(A_i)$, where $PD(A_i)$, is the set of probability distributions over actions A_i.

A. State Space

Feature 1: Program ID

Feature 2: Current Year

Feature 3: Current Month

Feature 4: Cost (APB) Status: for nine months, starting from the current month

Feature 5: Cost (Contract) Status: for nine months, starting from the current month

Feature 6: Schedule (APB) Status: for nine months, starting from the current month

Feature 7: Schedule (Contract) Status: for nine months, starting from the current month

Feature 8: Performance (APB) Status: for nine months, starting from the current month

Feature 9: Performance (Contract) Status: for nine months, starting from the current month

Feature 10: Funding (APB) Status: for nine months, starting from the current month

Feature 11: Funding (Contract) Status: for nine months, starting from the current month

Features 4–11 are represented by one of three colored bubbles (green, yellow, and red) in the Program Status page of the DAES report. Yellow bubbles refer to resolvable issues, and red bubbles refer to critical issues. If there is no issue, then the feature is represented by a green bubble. The number of bubbles starting from the current month indicates the number of months during which the issue is sustained. We assign the green, yellow, and red bubbles weights of 0.0, 0.1, and 1.0, respectively. Hence, in the feature value, the count of yellow bubbles will appear at the right side of the decimal point and the count for red bubbles will appear at the left side of the decimal point of the feature value. For example, consider the value of

Feature 4: Cost (APB) = 4.0. This value indicates that the Cost (APB) issue is critical and that it will continue to be critical for next consecutive four months after which time it is expected to be resolved.

B. Action Space

We capture both local and non-local actions.

Local Action 1 (LA1): PM takes action to resolve APB cost issue.
Local Action 2 (LA2): Contractor takes action to resolve contractor cost issue.
Local Action 3 (LA3): PM takes action to resolve APB schedule issue.
Local Action 4 (LA4): Contractor takes action to resolve contractor funding issue.
Local Action 5 (LA5): PM takes action to resolve APB/contractor funding issue.
Local Action 6 (LA6): PM takes action to resolve APB performance issue.
Local Action 7 (LA7): Contractor takes action to resolve contractor performance issue.
Local Action 8 (LA8): PM initiates inter-governmental dialogue to resolve the pertinent issue.
Non-Local Action (NLA): Coordinate with program *i.* (*i* refers to a neighbor program)

C. Transition Probabilities

When we extend this initial model to real data as part of out future work, the transition probability function will be computed empirically based on the past performance breaches of programs in the network. Accurate definition of this function will require large amounts of data about the performance and breaches of a large number of MDAP programs over long periods (e.g., monthly performance information for five or more years for 50 or more MDAPs would be a good place to start). Access to data at this scale will require automated analysis of the data sources, which is one of our goals for the next phase of the project.

D. Reward Function

The joint reward function is composed of local and global rewards. Local rewards are achieved both monthly and yearly. Also as part of future work, we

propose to calculate local reward value from the Acquisition Baseline Program section of DAES reports. The following two parameters (LR1 and LR2) capture the change in %PAUC and Schedule on a monthly basis. We use the following code to depict their changes:

If current %PAUC < 10% of the APB, then status = 0.

If 0 < current %PAUC < 10% of the APB, then status = +.

If 10% of APB < current %PAUC < 15% of the APB, then status = 1.

If current %PAUC > 15% of the APB, then status = 10 (breach has occurred).

Schedule: # of months beyond the threshold

LR1: PAUC_Monthly (APB)

LR2: Schedule_Monthly (APB)

To calculate the local reward value that is calculated yearly, we use the following parameters captured from SAR files:

LR3: APB Breach RDT&E (Values: 0/1)

LR4: APB Breach Procurement (Values: 0/1)

LR5: APB Breach Schedule (Values: 0/1)

LR6: APB Breach Performance (Values: 0/1)

LR7: APB Breach PAUC (Values: 0/1)

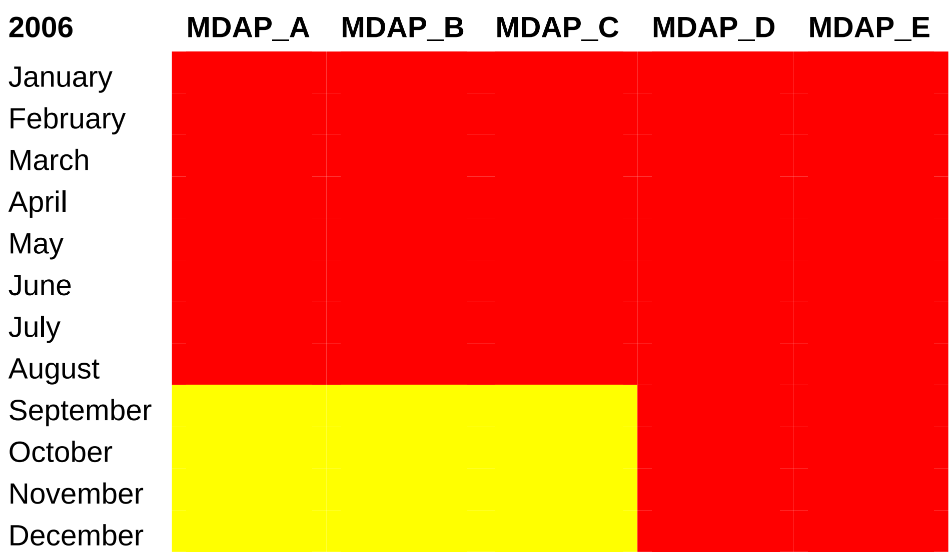
LR8: Nunn-McCurdy Breach PAUC (Values: 0/1)

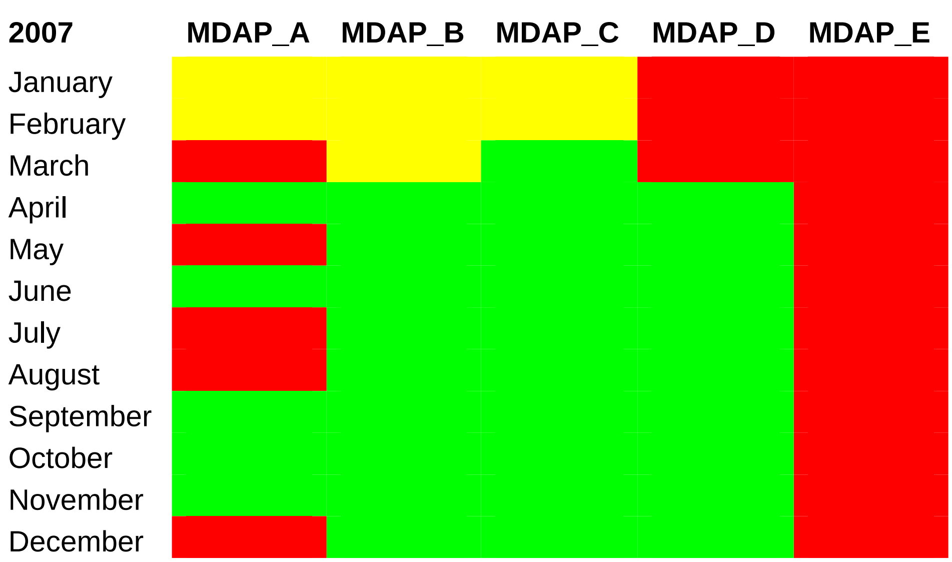
LR9: %PAUC (amount that appears in SAR)

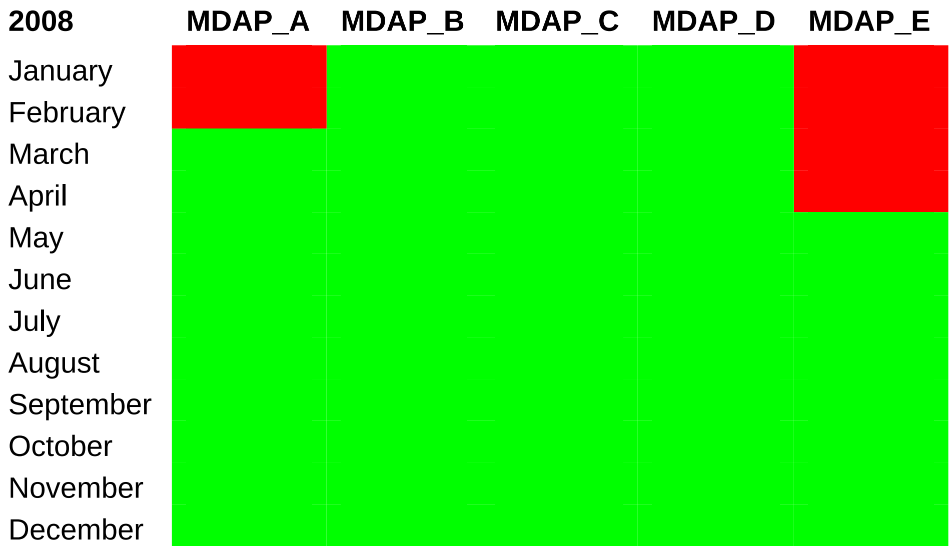
As part of another project, we are studying the viability of defining the global reward associated with an MDP state using the “centrality measure” from network theory (Newman, 2011) to capture the importance/influence the state has on cascading consequences downstream.

VIII. Understanding the Characteristics of the Existing Data

In this section we describe the importance of the DAES data set that facilitates deeper understanding about the dynamics of the MDAP network. We also enumerate the issues related to the quality of the data as well as its completeness and availability. We believe that by addressing these issues, the accuracy of the proposed decision-theoretic model will be enhanced.



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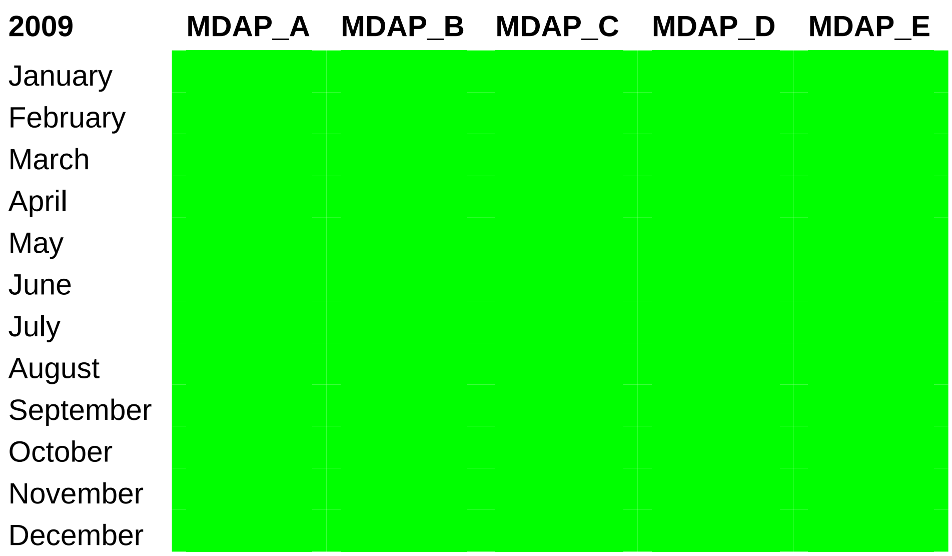
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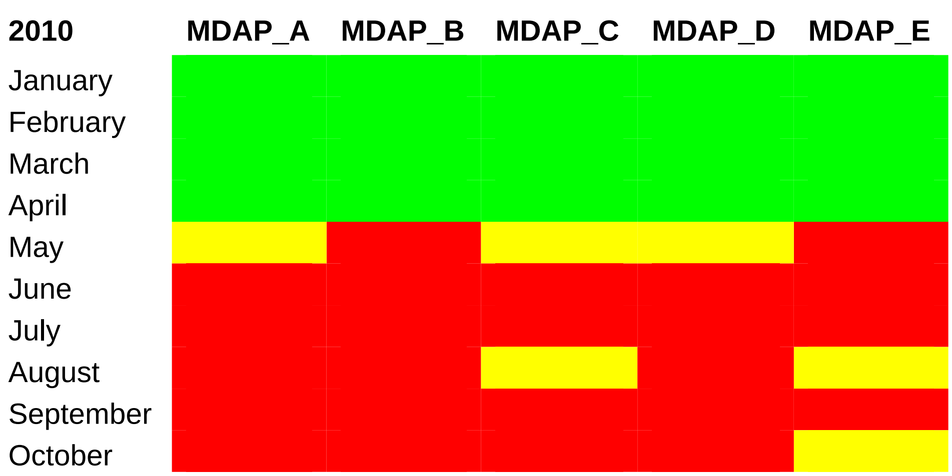
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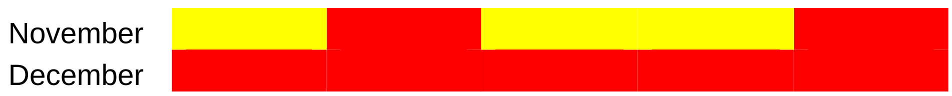

Figure 12. Completeness of MDAP_A 2006-2010 DAES data. Green = full report; yellow = partial report; red = no report

A. Significance of the Data Set

The available data that we used for in-depth study of the MDAP_A funding network offers significant insight into each individual program as well as the programs' interdependency relationships. DAES reports, which are published monthly, provide a granular view of the local issues pertaining to the program and the mitigation actions that have been taken to resolve the issues. Analyses of monthly forecasting on the program features help us to identify the root cause of the program issues locally. Failure to identify local root causes results in the search for non-local causes that originated through cascading effects. SAR files, on the other hand, provide a quantitative depiction of the program status on the basis of accrued breaches and of increases in %PAUC, cost, and funding figures. This resource helps us for comparative quantitative analyses and to gain insight about cascading effects.

B. Structure of the Data

- We note that none of the performance reports directly capture the interdependent regions.
- Although the PE documents (R-docs) provide a set of programs that share a common funding source, they do not provide a comparative status of the programs.
- The DAES reports show the data interdependency, but do not provide a summary status of the data neighbors.
- To determine the cascading effect between MDAP_A and MDAP_B, we had to build a "funding summary" table for both programs based on base year dollar. The existing SAR format provides only the then-year funding summary. For comparison and analyses, this table should be provided in terms of base year dollars.

- We observe that some DAES reports provide better understanding of the issues and mitigation measures, while others do not. There should be a uniform standard to prepare this document.

C. Availability of Data

- We observe that monthly DAES reports for the nodes in the MDAP_A funding network provide a very small spectrum of useful data for analyses. Although some programs report from 2006, the complete data set for all the members of the MDAP_A network is available only for 2008 and 2009. For 2007, only some programs possess complete reports. Some DAES reports provide partial information (contain only the risk summary page) and, hence, are not suitable for our analysis.

- So far, SAR seems to be the only resource that captures some aspects of interdependency. But the fact that SAR was not published in 2008 caused discontinuity in our analyses.

- We find that some programs stopped reporting after a certain time. Therefore, we had no way to learn the status of the program, even if it performed poorly. This unavailability problem appears to be a challenge for understanding interdependency issues.

IX. Challenges Due to Missing Data

This paper is based on the data that we received in August 2011. The funding network for MDAP_A based on the data analysis is shown in Figure 2. But the recent data that we received in October 2012 indicates that MDAP_A has only two neighbors: MDAP_C and MDAP_E (see Figure 13). This was because our initial data were based on neighborhood information extracted from PE reports. Later we found that there were inaccuracies in the data and had to correct the MDAP_A neighborhood information. Based on the updated network for MDAP_A, we have conducted a new study and investigated the DAES reports for the members of the updated MDAP_A funding network. In an effort to create an MDAP model, we extracted the state features for these member programs. Moreover, we have done manual data analyses to understand possible interdependency between the programs. In the manual analyses described in Figure 14, our aim was to categorize all observed issues that affected the programs and also to identify the interrelationship between the inter-program issues that could have triggered cascading effects. We went through the issue summary sections in the DAES documents, which are authored by different program managers, and identified the phrases that were categorized to cost, schedule, funding, and performance. For instance, “cost growth” and “unable to provide accurate cost forecast” were used to describe cost-related issues. We plan to use this manually extracted categorical information to train learning algorithms that will be used to extract relevant data automatically in our future work.

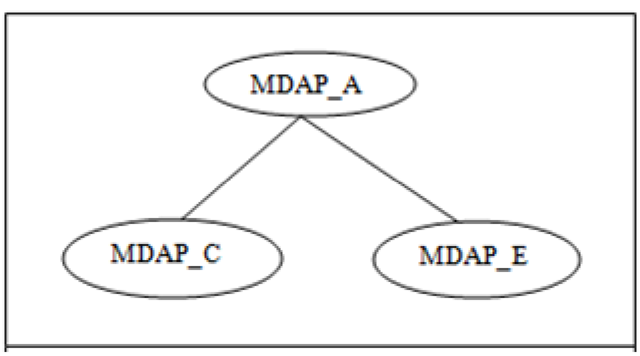

Figure 13. Updated MDAP_A Funding Network

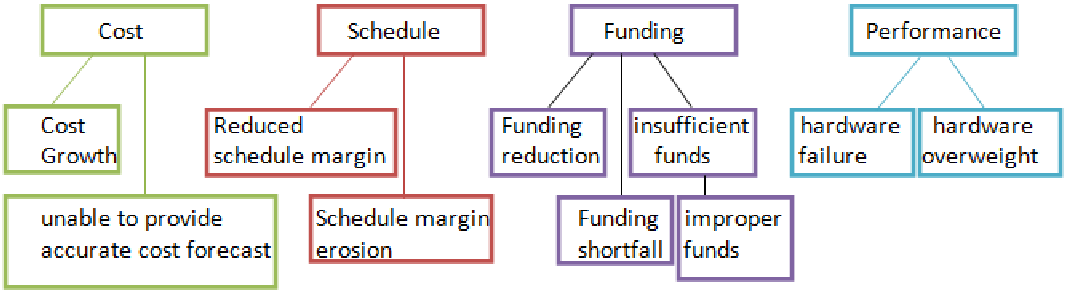

Figure 14. Categorization of the Issues as Captured From the DAES Reports for the Updated MDAP_A Funding Network

We now provide a flow diagram (Figure 15) that shows a potential cascading effect between MDAP_A (cost growth in 2007) and MDAP_C (funding shortfall in 2008). This observation, however, is neither conclusive nor complete unless we investigate the first-order funding partners of the program MDAP_C. Currently, we are extending our study over the first-order neighbors of the members of the MDAP_A funding network (Figure 13) so that these types of interdependencies can be better understood.

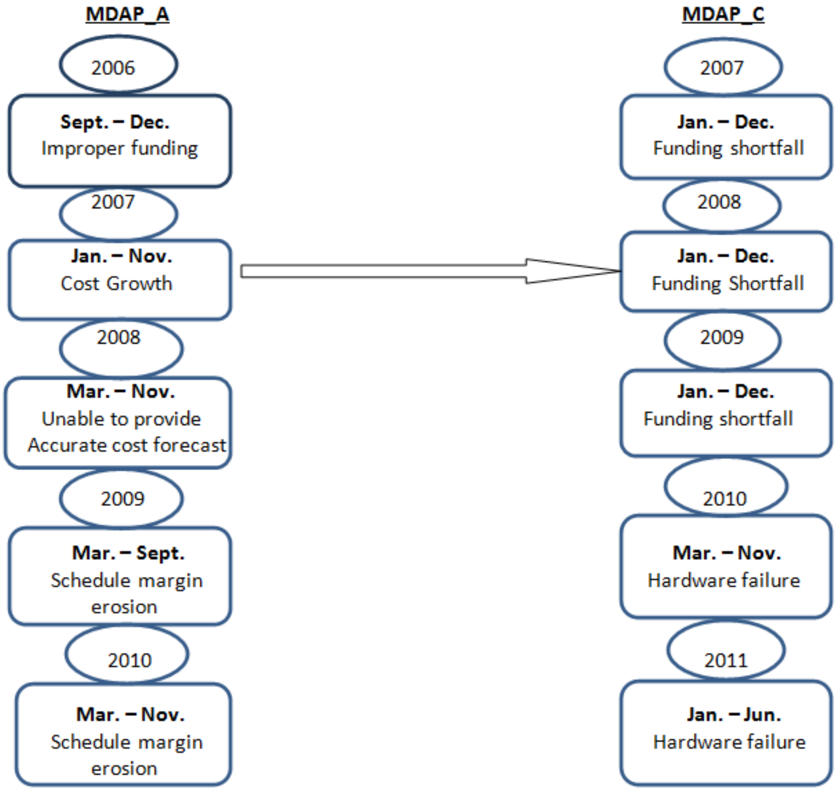

Figure 15. Flow Diagram for the Issues Related to MDAP_A and MDAP_C

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X. Conclusions and Future Work

We have conducted a case study of the MDAP_A funding network based on the available DAES and SAR files for the period from 2004–2010. Our analyses of these disparate yet intrinsically related data indicate that the programs are related to other programs based on funding and data relationships. This supported our belief that a network-centric predictive model would be a good candidate for MDAP performance analyses. We have also noticed that although the available data provide useful information about the MDAPs, it is challenging to integrate and understand these data coherently such that network dependencies can be revealed accurately.

We then observed that issues that led a program towards experiencing an APB breach and/or increase in %PAUC were not solely local and that the non-local issues might affect the performance of the program. We studied two related programs, MDAP_A and MDAP_B, from a local perspective based on their respective DAES reports and showed that local mitigation efforts, although successful at times, still resulted in APB breaches at other times. Specifically, we observed from the SAR files that the cost overrun of MDAP_A in 2009 onwards might have affected MDAP_B in 2010 in the form of a procurement funding shortfall. This observation, even if it may not be conclusive, is suggestive of cascading effects between neighboring MDAPs. Our study of MDAP_B in 2009 and 2010 led us to address two questions: (1) why would the procurement funding requirement increase in 2009 and 2010 and (2) what is the reason for MDAP_B not receiving its requested amount of funding that resulted in a funding shortfall condition for two consecutive years? Although the SAR files provide an answer to the first question, which is that the increase in quantity led to the need for increased funding, our data did not provide an answer to the second question. Hence it appears that this lack of knowledge about one's own program domain (not being

able to understand the root cause of the APB breach issues) may result in producing unexpected cascading effects through neighbor programs.

With respect to a formal model, we first argue why a decision-theoretic model based on MDPs would be a good candidate for isolating cascading risks for the MDAP network. We then show that the partially observable state space of each program warrants a DEC-POMDP model, which belongs to the class of MDPs. The computational complexity of the original DEC-POMDP led us to explore feasible approximations that would still provide the performance guarantees. We are currently working on automating this decision-theoretic model for the nodes in the MDAP_A funding network.

We believe that true joint capability relies on an understanding of the scope and challenges of the interdependencies among MDAPs. Our manual analyses of the DAES and SAR documents for a focused MDAP case study reveal indications about possible cascading effects and offer better understanding about the root causes for poor performance of the programs. In the future, we plan to automate this process based on the proposed DEC-MDP model, leveraging larger data sets. It would be important to observe how the second and higher order neighbors contribute to the cascading effects. We also plan to extend these analyses for MDAP data network focusing on data relationships that are relatively stable over multiple years.

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